On the Techno-economic Benefits of a Global Energy Interconnection

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ABSTRACT

The discussion about the benefits of a global energy interconnection is gaining momentum in recent years. The techno-economic benefits of this integration are broadly discussed for the major regions around the world. While there has not been substantial research on the techno-economic benefits, however, some initial results of the global energy interconnection are presented in this paper. Benefits achieved on the global scale are lower than the interconnections within the national and sub-national level. The world is divided into 9 major regions and the major regions comprise of 23 regions. When all the considered regions are interconnected globally, the overall estimated levelized cost of electricity is 52.5 €/MWh for year 2030 assumptions, which is 4% lower than an isolated global energy system. Further, the required installed capacities decrease by 4% for the fully interconnected system. Nevertheless, a more holistic view on the entire energy system will progress research on global energy interconnection as, synthetic power-to-X fuels and chemicals emerge as an important feature of the future sustainable global energy system with strong interactions of the power system not only to the supply, in energy fuel and chemicals trading globally, but also to the demand side. Global energy interconnection will be part of the solution to achieve the targets of the Paris Agreement and more research will help to better understand its impact and additional value.

Keywords: Global energy interconnection, 100% renewable energy, Solar energy, Wind energy, Synthetic fuels

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1. MOTIVATION FOR A GLOBAL ENERGY INTERCONNECTION

The global energy supply in the coming decades is framed by several challenges. Climate change mitigation requires defossilization of energy supply by mid-21st century to a net-zero greenhouse gas (GHG) emission society (IPCC, 2018). United Nations (2015) has framed development pathways for further progress in their Sustainability Development Goals. As, about 80% of the present energy supply is fossil fuel based (IEA, 2018), widely discussed GHG abatement strategy of fossil carbon capture and storage is highly costly (Child et al., 2018; Breyer et al., 2017), does not entirely avoid air pollution and heavy metal emissions (Buonocore et al., 2016; Epstein et al., 2011) and is neither a solution for the sectors where large point source capturing is not applicable, as in the transport sector. Bioenergy is limited in the global supply potential (Creutzig et al., 2015) and thus is not a major solution to the entire energy system.

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Efficiencies of the current fossil based thermal combustion processes are comparably low and thus favors a massive electrification of the overall energy system in the coming decades (Brown et al., 2018; Ram et al., 2019a). The main non-fossil electricity generation options are renewables and nuclear energy. Nuclear fission is a high-cost option (Schneider and Froggatt, 2018; Ram et al., 2018) and faces limited fuel supply for the existing technology (Barnaby and Kemp, 2007; EWG, 2013), whereas nuclear fusion has not achieved proof of concept and the long time-scales for installation, disqualifies it as an urgently needed solution to tackle climate change.

Renewable electricity has been utilized and expanded for more than 100 years for the case of hydropower to achieve an installed capacity base of more than 1100 GW for an excellent energy return on energy invested characteristics (Hall et al., 2014), based on highest technical lifetimes of all power generating technologies, however, further expansion potential is limited (Gernaat et al., 2017). Since the 2000s, two variable renewable electricity (VRE) technologies, solar photovoltaics (PV) and wind energy, have received very high growth rates of about 46% and 22% per year, respectively, leading to a total installed capacity of about 500 GW and 593 GW, respectively, by the end of 2018 (IEA-PVPS, 2018; GWEC, 2018). The advantage of these two major VRE technologies is their enormous scalability and huge resource potential (Perez and Perez, 2015), exceeding total global energy demand by orders of magnitude, particularly for the case of solar energy. The achieved cost level of about 20–25 €/MWh and 25–30 €/MWh for solar PV and wind energy at very good sites (FS-UNEP and BNEF, 2018; Vartiainen et al., 2019), brings both technologies to the forefront as a major source of energy in the 21st century. Due to violated sustainability guardrails of fossil and nuclear energy options (Child et al., 2018) and the limited potential of hydropower (Gernaat et al., 2017), a future energy system will be mainly built on solar and wind energy and thus will have high shares of renewables in the energy system. Table 1 provides an overview on literature reflecting sustainability guardrails and the true potential of VRE. The first detailed global 100% renewable energy system analysis has been presented by Sorensen (1996) as early as 1996, followed by Jacobson and Delucchi (2011) and Teske et al. (2011) in 2010/2011, with more comprehensive and detailed discussions since then.

The primary sectors in the global energy system are power, heat, transport and industry. Most of the present primary and final energy demand is not electricity-based (IEA, 2018; Ram et al., 2019a). However, massive direct and indirect electrification of the energy system in all of the aforementioned sectors can enable electricity as the major energy carrier in the future (Haegel et al., 2019). Technologies converting electricity to other forms of final energy and energy services are summarized as Power-to-X (PtX) technologies. These PtX technologies include power-to-heat (direct electric heat, electric heat pumps (Averfalk et al., 2017; Blarke, 2012)), power-to-water (reverse osmosis desalination (Caldera et al., 2016)), power-to-fuels/chemicals (hydrogen (Tremel et al., 2015; Götz et al., 2016; Fasihi and Breyer, 2020), methanation (Tremel et al., 2015; Götz et al., 2016; Fasihi et al., 2015; Varone and Ferrari, 2015), synthetic fuels (Varone and Ferrari, 2015; UBA, 2016; Fasihi et al., 2016), synthetic chemical feedstock (Kranenburg et al., 2026; Palm et al., 2016; IEA, 2017; Fasihi and Breyer, 2017)), a directly or indirectly electrified transport sector (Breyer et al., 2019a; Khalili et al., 2019) (battery electric vehicles (Garcia-Valle and Peças Lopes, 2013; Mahmoudzadeh Andwari et al., 2017), marine (Tzannatos et al., 2015; Horvath et al., 2018), aviation (UBA, 2016)) and power-to-CO_2 for negative emissions technologies (Breyer et al., 2019b; Fasihi et al., 2019; Breyer et al., 2019c), but also sustainable or non-avoidable carbon capture and utilization (CCU) (Farfan et al., 2019). A massive application of these technologies may lead to about

90% of electricity share in total primary energy supply (Ram et al., 2019a), clearly positioning electricity as the central energy carrier, but also establishing green hydrogen (Fasihi and Breyer, 2020) as the second most important energy carrier. Ram et al. (2019a) confirm that an energy system, mainly based on VRE, not only fulfils the sustainability criteria and the 1.5°C target, but does not lead to higher cost of the total energy system compared to the present, as well as creates several co-benefits, such as sustainable jobs (Ram et al., 2019b) and enormous water consumption from rivers reduction (Lohrmann et al., 2019), and stabilizes the total primary energy demand due to massive efficiency gains.

The state-of-the-art global energy system modelling for high shares of renewables in the energy mix reveals further insights that are not directly listed in Table 1. Modelling groups using Integrated Assessment Models (IAM) have not yet found pathways for highly renewable energy systems (Hansen et al., 2019), whereas groups using Energy System Models (ESM), as listed in Table 1 and tabulated by Khalili et al. (2019) for the transport sector, have already found pathways that integrate very high shares of renewables in the energy system. The limited progress of IAMs towards highly renewable energy pathways is obviously linked to the outdated cost assumptions for solar PV (Krey et al., 2019), as discussed in Vartiainen et al. (2019) and with consequences across the entire energy system including negative CO_2 emission technologies (Breyer et al., 2019c). This clearly indicates that more cooperation of these two almost distinct groups of modelers should be improved (Hansen et al., 2019). Teske (2019) and Ram et al. (2019a), report that their scenarios are compatible with a 1.5°C target, as set by the Paris Agreement. Natural climate solutions and negative emissions technologies are not yet standard in ESMs, since only Teske (2019) has systematically integrated natural climate solutions in their research and Ram et al. (2019a) report on the carbon sink potential of oil plants that can be grown on degraded land. Negative CO_2 emissions technologies (Fuss et al., 2018; Creutzig et al., 2019) are not yet included in any of the ESMs, which has to do with their core target of showing the merits of a highly renewable energy system, which already implies a zero GHG emissions system. However, specific temperature increase targets are not defined as the core optimization target. The ESMs have not yet implemented sustainable or unavoidable CO_2 point sources (in particular waste incinerators, pulp and paper industry, and limestone contribution for cement mill emissions) for their CCU and PtX features, since they assume either CO_2 direct air capture or CO_2 from biomass. The industrial feedstock sector is not yet well integrated by all the listed ESMs (Table 1).

The aforementioned outline of the future energy system is based on solid fundamental insights and respecting sustainability guardrails. However, it is not yet discussed what may be the optimized power system structure. Two poles are scientifically discussed and can be summarized as the Super Grid approach and a decentralized Smart Grid approach (Battaglini et al., 2009). The following paper will feature the Super Grid approach from major regions and continents to a global perspective, so that the potential of a global energy interconnection (Liu, 2015; GEIDCO, 2018; Jiang et al., 2018; Li and Jiang, 2018; Frick and Thioye, 2018; Wang et al., 2018) can be discussed.

2. TECHNO-ECONOMIC BENEFITS OF CONTINENTAL AND TRANS-CONTINENTAL ENERGY INTERCONNECTION

A global energy interconnection has been suggested first by Buckminster Fuller (1971). In 1992, the Global Energy Network Institute (Meisen, 1992) shifted the view for utilizing

TABLE 1
Global highly renewable energy system studies indicating the level of covering the desired aspects.*

	Model	Model type	Temporal resolution	Sectors	Pathway	Regions	Electricity exchange among regions	Energy trade among regions	RE share in 2050	long-term	Remark
Jacobson et al. (2018)	LOADMATCH, GATOR-GCMOM	optimization	hourly	all	overnight	20	no	no	100%	100%	1
Teske et al. (2018)	Mesap/PlaNet	simulation	annual	all	transition	10	no	no	100%	100%	2
Teske (2019)	Mesap/PlaNet	simulation	hourly/annual	all	transition	72	no	no	100%	100%	1
Bogdanov et al. (2019a)	LUT model	optimization	hourly	power	transition	145	partly	no	99.7%	100%	
Ram et al. (2019a)	LUT model	optimization	hourly	all	transition	145	partly	no	99.9%	100%	1
Löffler et al. (2017)	GENeSYS-MOD	optimization	time slices	power, heat, transport	transition	10	no	fuels	100%	100%	
Pursiheimo et al. (2019)	VTT-TIMES	optimization	time slices	all	transition	13	no	no	84.1%	84.1%	3
Deng et al. (2012)	Ecofys	simulation	annual	all	transition	1	no	no	95.0%	95%	
Sgouridis et al. 2016)	NETSET	simulation	annual	all	transition	1	no	no	90.7%	98.3%	4

* Latest versions of articles of the respective groups are listed. Two research pieces not yet published in journals are added which indicate further progress of the two groups.
1 industrial feedstock is missing.
2 non-energy use of 9620 TWh_{th} still fossil.
3 model is unable to defossiliate non-energetic industrial demand.
4 remaining non-renewable is nuclear energy.
Source: The table is adapted from Hansen et al. (2019).

renewable energy sources. Kurokawa et al. (Kurokawa, 2007; Komoto et al., 2009) linked the concept of a global grid to the abundant global solar energy resource available. Chatzivasileiadis et al. (2013) have discussed the concept of a global grid further and added considerations of operation and regulation. Liu (2015) further lifted the discussion on global energy interconnection to a major research topic in recent years.

In recent years all major regions across the world have been studied for their Super Grid benefits (Breyer et al., 2017). The most widely researched major regions in the world for very large-scale grid interconnection has been Europe and North Africa. The research began as early as in the 1920s for the Atlantropa project, suggested by Sörgel (Sörgel, 1932; Voigt, 2007), converting the Mediterranean into a huge hydropower plant with massive negative environmental consequences. Already at that time a solar PV based Super Grid has been suggested by a Siemens researcher (Dominik, 1930). The concept of integrating the power systems of Europe and Africa had been taken up again in the 1960s utilizing the vast hydropower potential of Grand Inga (Justi, 1960). However, environmental concerns (Winemiller et al., 2016) made this idea unrealistic, amplified by rising doubts of the economic performance, as pointed out by Oyewo et al. (2018), since fast cost decline of VRE may offer a more convincing alternative. In 1980s, hydrogen has been linked to solar energy (Winter, 1981; Sprengel and Hoyer, 1989), which has been for the first time a comprehensive energy system concept for all energy sectors. In the 1990s and 2000s, the DESERTEC Foundation (started as Trans-Mediterranean Energy Cooperation) and the German Aerospace Center rekindled the idea of the energy system integration of Europe and North Africa (Trieb et al., 2006; 2012; Knies, 2009) as a means of co-operative benefits for the involved countries, mainly utilizing concentrating solar thermal power, which had been the least cost energy source of solar electricity at that time. Czisch (2005) had been the first who showed the benefits of a 100% renewable energy integration of Europe, Western Eurasia, Middle East and North Africa in a ground-breaking methodological advanced research of hourly modelling, which has not yet become the scientific standard even after 15 years, but which is now the basis of all state-of-the-art research in the field. The Desertec project has received much attention since the Desertec Industrial Initiative (Dii) was formed in late 2000s and major reports were published in the 2010s (2012; 2014). It has been also found that 90% of humankind lives within 3000 km to major deserts Breyer and Knies, 2009; Breyer, 2012), which further highlights the supply potential of solar energy. The Dii reports highlighted again after many decades that solar PV may be a major source of electricity for a modern large-scale energy integration.

The second most researched major regions in the world had been Northeast Asia (Komoto et al., 2009; Mano et al., 2014; Song, 2012; 2014; Komoto et al., 2013; Breyer et al., 2015) and an East Asian energy interconnection from Australia to China (Taggart et al., 2012). The vast solar and wind energy potential in Australia and the huge energy demand in the highly populated regions of East Asia could create substantial benefits for all involved countries (Taggart et al., 2012; Blakers et al., 2012; Gulagi et al., 2017a; Wang et al., 2018). An integration of Northeast Asian countries may utilize the vast solar and wind energy potential of Western China and Mongolia, which are rather low populated regions, for the high populated regions in East China, Korea and Japan.

Most of the studies mentioned above outline the energetic benefits of the Super Grid approach, but often lack in comparative economic analyses showing that a Super Grid approach would lead to lower energy system cost than a decentralized energy system. The team of Breyer showed in recent years that major regions in the world would benefit from a Super Grid approach (Breyer et al., 2017). Detailed studies have been carried out for Europe (Child et al., 2019; Breyer et al., 2016), Eurasia (Bogdanov and Breyer, 2015), MENA (Aghahosseini et al., 2016; 2019a), Sub-Saharan Africa (Oyewo et al., 2018; Barasa et al., 2018), SAARC (Gulagi et al., 2017a), Northeast Asia (Bogdanov and Breyer, 2016), Southeast Asia and the Pacific Rim (Gulagi et al., 2017b), North America (Aghahosseini et al., 2017) and South America (Barbosa et al., 2017). This comprehensive research has been carried out in three standard scenario designs: region-wide, country-wide and area-wide integration, which revealed an increasing economic energy system integration benefit from a sub-national level (region-wide) to a national level (country-wide) of about 7.2% in global average and a further cost reduction potential of 4.5% from the national level to a major region level (area-wide). These results are summarized in Table 2.

The cost optimization of the major region analyses is based on two fundamental equations describing the target function for the least cost optimization (Equation 1) and the energy balance (Equation 2), as summarized by Bogdanov et al. (2019a).

$$\min\left(\begin{array}{l}\sum_{r=1}^{\mathbf{reg}}\sum_{t=1}^{\mathbf{tech}}\left(CAPEX_t \cdot crf_t + OPEXfix_t\right)\cdot instCap_{t,r} \\ +OPEXvar_t \cdot E_{\mathrm{gen}\ t,r} + rampCost_t \cdot totRamp_{t,r}\end{array}\right) \tag{1}$$

The target function of the applied energy model for minimizing annual costs comprises all hours of a year using the abbreviations: sub-regions (*r,* **reg**), generation, storage and transmission technologies (*t,* **tech**), capital expenditures for technology *t* ($CAPEX_t$), capital recovery factor for technology *t* (crf_t), fixed operational expenditures for technology *t* ($OPEXfix_t$), variable operational expenditures technology *t* ($OPEXvar_t$), installed capacity in the region *r* of technology *t* ($instCap_{t,r}$), annual generation by technology *t* in region *r* ($E_{\mathrm{gen}\ t,r}$), cost of ramping of technology *t* ($rampCost_t$) and sum of power ramping values during the year for the technology *t* in the region *r* ($totRamp_{t,r}$).

The main constraint for the optimization is the matching of power generation and demand for every hour of the applied year. For every hour of the year the total generation within a sub-region and electricity import cover the local electricity demand.

$$\begin{aligned}\forall h \in [1,8760] \sum_{t}^{\mathbf{tech}} E_{\mathrm{gen}\ t} + \sum_{r}^{\mathbf{reg}} E_{\mathrm{imp}\ r} + \sum_{t}^{\mathbf{stor}} E_{\mathrm{stordisch}\ t} = \\ E_{\mathrm{demand}} + \sum_{r}^{\mathbf{reg}} E_{\mathrm{exp}\ r} + \sum_{t}^{\mathbf{stor}} E_{\mathrm{storch}\ t} + E_{\mathrm{curt}} + E_{\mathrm{other}}\end{aligned} \tag{2}$$

Equation 2 describes constraints for the energy flows of a sub-region. Abbreviations: hours (*h*), technology (*t*), all modelled power generation technologies (*tech*), sub-region (*r*), all sub-regions (**reg**), electricity generation (E_{gen}), electricity import (E_{imp}), storage technologies (**stor**), electricity from discharging storage ($E_{\mathrm{stordisch}}$), electricity demand (E_{demand}), electricity exported (E_{exp}), electricity for charging storage (E_{storch}), electricity consumed by other sectors (Heat, Transport, Desalination, Industrial fuels production, CO_2 removal) (E_{other}), curtailed excess energy (E_{curt}). The energy loss in the high voltage direct current (HVDC) and alternating current (HVAC) transmission grids and energy storage technologies are considered in storage discharge and grid import value calculations.

The Super Grid results highlighted in Table 2 clearly reveal the enormous benefits of the Super Grid approach. The most remarkable research result is the cross-border electricity trade from the highly decentralized approach (region-wide) to the Super Grid approach (area-wide) of 17%. This means that 83% of all electricity should be generated regionally close to the demand centers for achieving cost-optimized electricity supply. This result has been achieved across all major regions in the world within a range of 6% (Southeast Asia) to 24% (North America). Consequently, it can be concluded that the cost optimized power system shows mainly decentralized characteristics which are further supported by centralized elements of a Super Grid to achieve a least cost solution, which leads to the concept of a Super Smart Energy System, which is discussed in more detail in Child et al. (2019).

The main research question of this paper is 'What are the techno-economic benefits of integration of the major regions to super region clusters or an integrated global energy interconnection'. The hypothesis is that a further integration benefit is observed as shown in Table 2 from a two-level integration of sub-national regions to countries and major regions. There is not enough research on the cost benefits of clusters of major regions, except the Desertec approach of integrating Europe and North Africa, however, there are not many studies comparing the benefits of a centralized vs decentralized energy system options, since almost all techno-economic studies have been carried out for the centralized case, neglecting a comparison to the decentralized case. The integration of at least two major regions have been carried out for the case of East Asia (integrating Northeast Asia and Southeast Asia) (Gulagi et al., 2017a), Americas (integrating North America and South America) (Aghahosseini et al., 2019b) and for three major regions of Europe, Eurasia and Middle East and North Africa (Bogdanov et al., 2016), which did for the first time a recalculation of the earlier research of Czisch (2005). The results of the super region clusters clearly disapprove the hypothesis of further substantial integration benefit, since the additional economic benefit of a power system integration is limited to 0.4% (East Asia), 1.6% (Americas) and 1.3% (Europe-Eurasia-MENA). Such low benefits may not outweigh the substantial efforts of further grid integration, since the higher complexity of the system is not anymore covered by substantial additional benefits. These results indicate that the economic optimum for geo-spatial power sector integration can be achieved on the level of major regions. A global energy interconnection may be still beneficial, but the respective electricity trade can be expected to be more within the major regions. Additional risk for less developed and less stable counties my increase the cost of capital for parts of a super region cluster, which may further reduce the limited benefit, as discussed by Egli et al. (2019) and Bogdanov et al. (2019a; 2019b). Practically all global energy system analyses assume uniform cost of capital assumptions, which is recognized as a clear deficit and research gap, since it is consequence of a lack of methods for projecting cost of capital for future periods (Egli et al., 2019; Bogdanov et al., 2019b).

There is limited research on techno-economic considerations of a global energy interconnection, since most existing research is limited to energetic considerations, the technical feasibility and outlining the vision (Chatzivasileiadis et al., 2013; Aboumahboub et al., 2012; Biberacher, 2004). Dahl et al. (2017) carry out a global 100% renewable energy based grid analysis for the Northern Hemisphere and find that Europe may reduce its electricity cost in trading with nearest neighbors, but they do not find benefits for longer distance electricity exchange due to too high power transmission cost. It can be assumed that the found benefits are even overstated, since no storage options are applied and no dispatchable renewables are considered, whereas both would reduce the value of long distance power transmission. The next

TABLE 2

Overview on major region results for LCOE, generation, storage and cross-border trade for the scenarios region-wide, country-wide and area-wide.

	Population	Electricity demand	LCOE			generation			storage contribution for demand			trade of demand	
			region	country	area	region	country	area	region	country	area	country	area
	[mil]	[TWh]	[€/MWh]	[€/MWh]	[€/MWh]	[TWh]	[TWh]	[TWh]	[%]	[%]	[%]	[%]	[%]
Europe	675	4183	73	73	64	4671	4671	4356	16.6	16.6	11.3	0	14
Eurasia	244	1450	63	57	53	1771	1681	1613	3.5	5.4	5.6	12	20
MENA	529	1813	61	61	55	2107	2107	1999	18.2	18.2	11.2	0	12
Sub-Saharan Africa	1384	866	58	58	55	981	980	961	15.2	13.6	13.3	1	9
SAARC	1922	2597	72	70	67	2948	2865	2818	23.7	22.8	20.9	6	14
Northeast Asia	1546	9878	63	55	56	11438	10953	11077	20.2	15.7	15.6	12	11
Southeast Asia	646	1630	67	66	64	1780	1773	1714	19.9	18.0	17.0	1	6
North America	558	6059	63	56	53	7207	7062	6861	20.7	14.8	13.2	18	24
South America	445	1813	62	59	55	2207	2026	1918	12.9	12.4	8.3	9	12
World	7949	30289	65.0	60.3	57.6	35110	34118	33317	20.8	19.0	16.1	8	17

Sources: Data are taken from (Breyer et al., 2016; Bogdanov and Breyer, 2015; Aghahosseini 2016; 2017; 2019a; Barasa et al., 2018; Gulagi et al., 2017b; 2017c; Barbosa et al., 2017).

step of common research effort has to take more into account the economics of global energy interconnection. One of the very few techno-economic considerations of a global energy interconnection is shown in Figure 1. To the knowledge of authors, it is the only existing research for a global energy interconnection based on 100% renewable electricity and it is carried out in full hourly resolution. The world is structured into 23 main regions, the resource assessment uses the methods of Bogdanov and Breyer (2016) and the same technical and economic assumptions, whereas load assumptions and other assumptions can be found in more detail in the major research (Breyer et al., 2016; 2017; Bogdanov and Breyer, 2015; Aghahosseini 2016; 2017; 2019a; Barasa et al., 2018; Gulagi et al., 2017b; 2017c; Barbosa et al., 2017). The scenario design uses the overnight approach and technical and financial assumptions for the year 2030. The 23 regions can be also integrated into the 9 major regions as typically reported in research of Breyer and Bogdanov et al.

An interesting fundamental finding is that a power system integration for 23 regions in the world is already highly optimized. The global average levelized cost of electricity (LCOE)

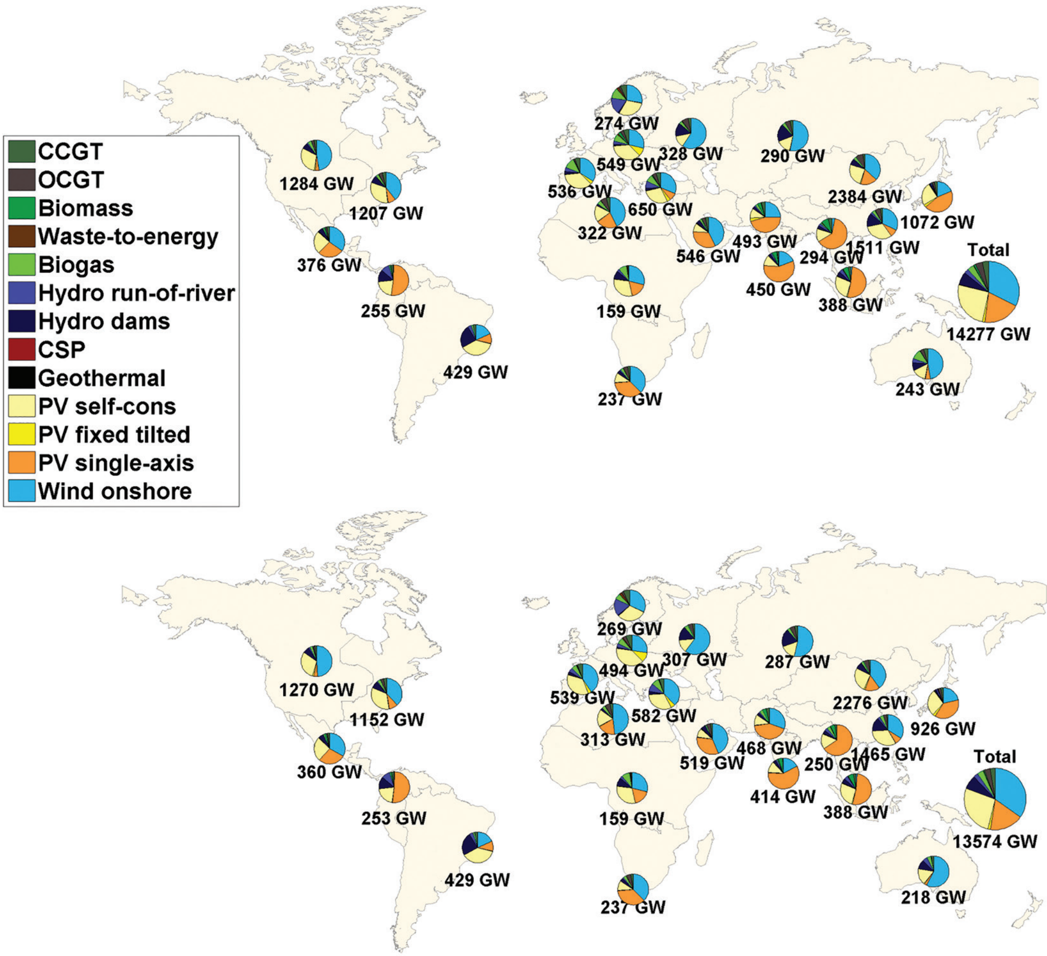

FIGURE 1
Installed capacities for a fully renewable electricity system for 2030 assumptions for the 23 single regions (top) and global energy interconnection (bottom).

for all 23 regions treated as single regions without electricity interconnection between them leads to 54.3 €/MWh. If the 23 regions are interconnected on the level of the 9 major regions, which practically means the electricity exchange option for two to three neighboring regions (see Table 2), then the cost can only be marginally reduced to 53.5 €/MWh (–1.3%). The full global energy interconnection of the 23 regions leads to a total LCOE of 52.5 €/MWh (–2.0% vs 9 major regions and –3.3% vs 23 single regions), as depicted in Figure 2. These results confirm the trend of cost reduction in large-scale interconnection, however, the relative cost advantage is substantially smaller. This may lead to the conclusion that the largest power system integration benefit may be already realized in interconnecting the 145 regions of the full LUT model (Breyer et al., 2017; Bogdanov et al., 2019a) to 23 regions, whereas a further level of interconnection does not lead anymore to substantial cost reduction. Such a possible effect should be more analyzed in future research. The relative distribution of the global weighted average total system LCOE of 52.5 €/MWh shows least cost in Australia, China South, Russia West and Europa Atlantic of about 45–46 €/MWh and highest cost in India, Mekong region and Japan/ Korea of about 62–69 €/MWh. A global energy interconnection does not lead to a global uniform cost level, since the power line interconnection adds to the cost, which requires respectively lower electricity generation for an overall cost reduction.

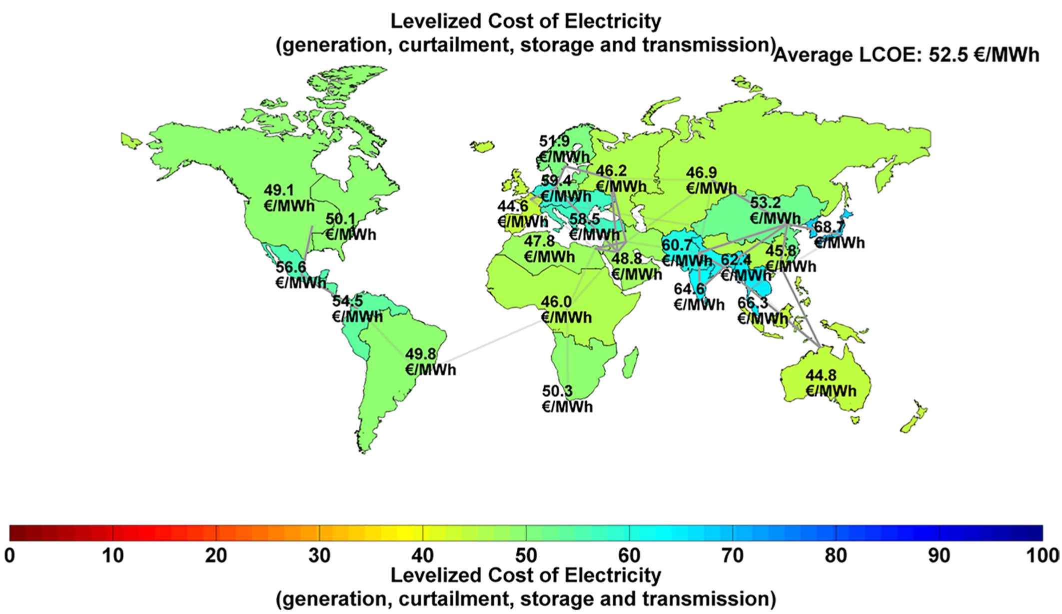

FIGURE 2

Distribution of total system LCOE for global energy interconnection on the 23 regions which are allowed to exchange electricity.

The findings for the total system LCOE are confirmed by other metrics, such as the total generated electricity for the given demand which is about 33,120 TWh (23 single regions), 32,920 TWh (9 major regions) and 32,430 TWh (global energy interconnection). Wind energy slightly benefits from a large-scale energy interconnection, as the global wind energy generation share rises from 44% (23 single regions) to 46% (global energy interconnection) and the solar PV share declines from 35% to 33%, respectively. The effect of increasing wind energy for large scale integration shall not be overestimated, since energy transition research revealed that the fast cost decline of solar PV and batteries (Vartiainen et al., 2019) may lead in the period from 2030 to 2050 to a substantially higher solar PV share in total electricity supply (Ram et al., 2019a; Bogdanov et al., 2019a). The equivalent power generation capacity values for 2030 confirm the trend of reduced electricity generation requirement as a function of increasing geospatial interconnection, since the total installed capacity can be reduced from about 14,280 GW (23 single regions) to about 13,570 GW (global energy interconnection), which allows a reduction of 5.0% of the power capacities for an optimized utilization in the global energy interconnection, which in turn requires power transmission capacity to enable cross-border electricity exchange among the regions. The global energy interconnection does not significantly reduce the curtailment since 4.7% of curtailed electricity (23 single regions) is only improved to 4.1% (global energy interconnection). There is a trade-off between storage and cross-border electricity exchange, since 14.7% of all electricity demand supplied by storage (23 single regions) declines to 13.7% (9 major regions) and further declines to 13.3% (global energy interconnection), whereas the share of cross-border electricity exchange achieved is 3.5% (9 major regions) and 4.4% (global energy interconnection).

The role of storage is not much discussed in this paper, but detailed description can be found in (Breyer et al., 2016; 2017; Bogdanov and Breyer, 2015; Aghahosseini 2016; 2017; 2019a; Barasa et al., 2018; Gulagi et al., 2017b; 2017c; Barbosa et al., 2017). Koskinen and Breyer (2016) provide insights on the role of storage in global and transcontinental energy system studies. These results confirm the value of power interconnection, however, the highest benefit can be achieved for interconnecting the world structured in 145 regions to 23 regions, whereas the additional value of further power system integration seems to be rather limited, but cost decline through interconnection can be still observed.

The specific HVDC transmission grid losses are assumed to be 1.6%/1000 km and 1.4% per HVDC converted pair as applied in Bogdanov and Breyer (2016). Transmission losses of the major region integration as detailed in Table 2 are in the global average 4.1% of the transmitted electricity, within a range of 2.9% in the SAARC region and 6.7% in Europe, whereas the loss as ratio to total electricity demand is in the global average 0.8%. About 17% of total electricity demand is transmitted via the HVDC overlay grid in the major region design. About 4% of total electricity demand is cross-regionally exchanged in the global energy interconnection structuring of the 23 regions as visualized in Figure 3. The average levelized cost of transmission of the area-wide major region integration comprises about 5.6% of the total levelized cost of electricity in the global average, whereas the total investment cost can be reduced by about 10.6% for the area-wide major region integration compared to the region-wide system design, which clearly indicates the value add of the respective investments for the HVDC transmission grid integration.

Figure 3 visualizes the regional structuring of the 23 regions and the allowed power interconnections. The chosen points of interconnection are either the load center of the respective region or a geographic mean area. Power interconnections which generate benefits within the chosen model setup are shown in white color, whereas offered power interconnection without realized cost benefits, and thus not used, are colored in red. It can be observed that in the structure of the 23 regions no cost reduction for the total energy system can be found for interconnections across the Atlantic (neither North nor South), Pacific and North Pole. Purvins et al. (2018) found a small benefit of interconnecting North America and Europa via Iceland, whereas an updated cost assumption on low-cost local solar PV and battery (Vartiainen et al., 2019), but also wind energy (Bogdanov et al., 2019a) may remove the found small benefit. The evenly distributed renewable energy resources in Sub-Saharan Africa limit the value add of power interconnection between Central Africa to Southern Africa. The long distances for power interconnection between Australia and Southeast Asia to neighboring regions do not generate a value add in the chosen structure of the 23 regions. Still, it has to be noted that a power interconnection of Australia and Singapore has been proposed recently (Chin, 2019), which may include more considerations than only economic ones. The Americas are interconnected, as well as Europe, Eurasia, North Africa, Central Africa, Middle East, Pakistan, India, China, Central Asia/ Siberia and Japan/ Korea, while Southern Africa and Australia with Oceania are mostly autonomous from the global grid. In total three major grid clusters are formed: Americas, Europe-MENA-Central Africa and Asia, with interconnection between last two. The results clearly show that close neighboring regions can realize a cost reduction in most cases by allowing power interconnection, whereas benefits from very long-distance power interconnection across the oceans could not be found.

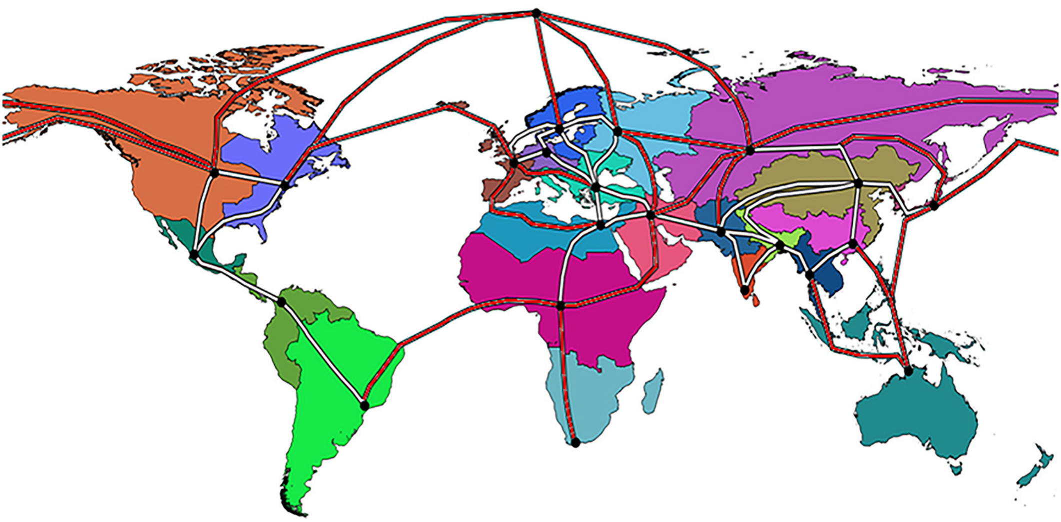

FIGURE 3
Global energy interconnection for the world structured in 23 regions. The modelling is done in full hourly resolution for the case of 100% renewable energy for 2030 technical and financial assumptions. White colored interconnections generate benefits to the total energy system, whereas red colored power lines cannot contribute to further cost reductions. The node in the very north represents a possible power interconnection via the North Pole.

The used aggregation algorithm (Bogdanov and Breyer, 2016) for solar PV and wind energy depends on the size and structure of regions, since the best sites in a region are aggregated. This effect can lead to an increase or decrease in full load hours (FLH) of solar PV and wind energy. The difference for fixed-titled solar PV from 145 regions linked with power lines to 92 countries to 23 macro regions is only +0.2% higher FLH, whereas one can find for solar PV single-axis tracking an increase of 4.1% in FLH and for wind energy a decline of –2.8% in FLH. These deviations seem to be manageable, however, for better comparability of the results, modifications shall be applied to reduce the impact of this effect to a minimum level in future research. An appropriate method would be the resource assessment for the 145 regions, aggregated to 92 countries, and then using the relative resource utilization values of the 145 regions as a weighting factor for the aggregation to larger regions.

First research insights are available for global energy interconnection of electricity-based products, which do not need power transmission interconnections for global trade. Even existing global trade infrastructure of the fossil fuel based energy system can be used in the future. The coal-based infrastructure cannot be used and will end as stranded assets, however, the oil and gas infrastructure may have some value. Heuser et al. (2019) investigate electricity-based hydrogen export from Patagonia to Japan, whereas Gulagi et al. (2017a) have found benefits of converting electricity to synthetic natural gas (SNG) which requires liquefaction, long-distance transport and regasification for the case of Australia and Northeast Asia. However the same paper could not confirm the benefits for cross-border exchange of electricity for the same exporting and importing regions. Fasihi et al. have shown substantial benefits of international trade of PtX products, as shown for liquefied SNG (Fasihi et al., 2015), Fischer-Tropsch liquid fuels (Fasihi et al., 2016), methanol and dimethyl ether (Fasihi and Breyer, 2017), ammonia (Fasihi et al., 2020), and indicated similar characteristics for all hydrogen-based synthetic fuels and chemicals (Fasihi and Breyer, 2020; Fasihi et al., 2017). All these examples utilize at least at some point the existing infrastructure. A recent report on PtX trade also highlights the merits of international cooperation and trade of respective synthetic fuels (WEC, 2018).

3. LIMITATIONS OF RESEARCH

The state-of-the-art research has improved substantially in recent years, in particular 100% RE research is now established as an own research field (Hansen et al., 2019), full hourly modelling is standard for cutting-edge ESMs and almost all energy sectors can be modelled in high geo-spatial and temporal resolution. However, no research exists for a full energy system including industrial feedstock representing the main industries for a highly renewable energy system. This is required to show in a comprehensive way the features of a full global energy interconnection for all final energy demands in high geo-spatial and temporal resolution as an energy transition from the present to 2050. The dominating energy carrier in a future energy system will be electricity as primary energy and also as final energy, complemented by hydrogen as most valuable platform energy carrier (Ram et al., 2019a; Fasihi and Breyer, 2020). Whether hydrogen will be much traded on a global scale will depend on technical developments for efficient hydrogen transport, in particular in the form of liquefied hydrogen. Other final energy demand fuels will be liquefied SNG, synthetic liquid fuels and the two main bulk chemicals methanol and ammonia. A comprehensive global energy interconnection modelling has to be structured in high geo-spatial resolution and allows a full power interconnection of all regions, but also the other main energy carriers, in particular hydrogen, SNG, synthetic liquid fuels, methanol and ammonia, so that the global energy system for all sectors is represented.

The current low-cost electricity sources solar PV and wind energy are available for 20–25 €/MWh and 25–30 €/MWh at excellent sites in the world (Vartiainen et al., 2019; FS-UNEP and BNEF, 2018). It is expected that solar PV can achieve cost levels of about 10 €/MWh in the 2020s (Vartiainen et al. 2019). Electricity available at such a cost level can enable high full load hours for PtX applications, in conjunction with low-cost electrolyzers, since hydrogen buffer storage can decouple variable renewable electricity availability from baseload hydrogen demand of synthesis units in a two-step power-to-hydrogen and a hydrogen-to-X process (Fasihi and Breyer, 2020). This system can be potentially further boosted by low-cost batteries which could help to lift the full load hours of CO_2 direct air capture for efficient hydrogen-to-X processes (Breyer et al., 2019b; Fasihi et al., 2019; Breyer et al., 2019c). The megatrend of very low-cost renewable electricity and its conversion in PtX processes will have an impact on the global energy interconnection at the supply side with electricity transmission, in transportation of these fuels and chemicals and at the demand side. A comprehensive global energy interconnection modelling will have to capture these new global energy trade pattern.

Another effect requires more attention in global energy interconnection research: competition of long-distance power transmission with very low-cost electricity generation and low-cost storage technologies. Cost decline of solar PV is linked to learning rates of about 25% in the long-term and PV module learning rates of close to 40% were observed in the last 10 years (Vartiainen et al., 2019; ITRPV, 2019). Respective learning rates for battery storage and electrolyzers are around 15% (Schmidt et al., 2017). The relative cost decline of power transmission technologies are much lower and not comparable to the above mentioned technologies. These trends lead to a relative decline in competitiveness of long-distance power transmission and more locally and regionally structured energy systems. Understanding the sensitivities of such long-term cost decline trends on the structure of the global energy interconnection will be rewarding for anticipating most beneficial long-term cooperation for international energy trade.

4. CONCLUSIONS

Existing research clearly finds economic benefits of a power system integration of decentralized regional systems for a major region and on a continental level, whereas for clusters of major regions a global electricity interconnection cannot generate comparable additional benefits. This study represents the very first results of a global energy interconnection, including 9 major regions and 23 regions, calculated in full hourly resolution and for achieving highest levels of sustainability. The calculated levelized cost of electricity for an entirely interconnected energy system globally is 52.5 €/MWh, which is 4% lower than an isolated global energy system. Although smaller benefits can be achieved via long-distance grid interconnections globally, the results suggest that the higher complexity of the system can be only marginally covered by additional economic benefits.

Long-distance energy trading in a future energy systems respecting sustainability guardrails may happen in the form of high-density energy carriers, in particular liquefied SNG, synthetic liquid fuels, methanol and ammonia, whereas further technology progress for liquefied hydrogen may be needed for establishing global hydrogen value chains and respective trading.

Comprehensive global energy interconnection research should enlarge the scope of energy from electricity to all relevant energy carriers of a sustainable future energy system, namely synthetic hydrocarbons (SNG, Fischer-Tropsch liquid fuels), methanol, ammonia and liquefied hydrogen. A high global granularity of geo-spatial structuring may reveal the relative range of economic benefits generated by power transmission, which may be complemented by progress in understanding future trade patterns for renewable electricity-based PtX fuels and chemicals and their respective transportation costs. Substantially more research for global energy interconnection in high geo-spatial resolution and full hourly resolution of a highly renewable energy system is needed, in particular also for its techno-economic features.

The global energy system has to achieve zero GHG emissions till the mid-21st century, fulfil the Sustainability Development Goals of United Nations and respect the concept of sustainability guardrails. Global energy interconnection will be part of the many solutions and more research will help to better understand its impact and additional value.

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References

Aboumahboub T., Schaber K., Wagner U., Hamacher T. 2012. "On the CO_2 emissions of the global electricity supply sector and the influence of renewable power-modeling and optimization," *Energy Policy* 12: 297–314. https://doi.org/10.1016/j.enpol.2011.11.088.

Aghahosseini A., Bogdanov D., Breyer C. 2016. "The MENA Super Grid towards 100% Renewable Energy Power Supply by 2030," *11th International Energy Conference*, Tehran, May 30–31.

Aghahosseini A., Bogdanov D., Breyer C. 2017. "A techno-economic study of an entirely renewable energy based power supply for North America for 2030 conditions," *Energies* 10: 1171. https://doi.org/10.3390/en10081171.

Aghahosseini A., Bogdanov D., Breyer C. 2019a. "Towards sustainable development in the MENA region: analysing the feasibility of a 100% renewable electricity system by 2030," submitted.

Aghahosseini A., Bogdanov D., Barbosa L.S.N.S., Breyer C. 2019b. "Analysing the feasibility of powering the Americas with renewable energy and inter-regional grid interconnections by 2030," *Renewable and Sustainable Energy Reviews* 105: 187–205. https://doi.org/10.1016/j.rser.2019.01.046.

Averfalk H., Ingvarsson P., Persson U., Gong M., Werner S. 2017. "Large heat pumps in Swedish district heating systems," *Renewable and Sustainable Energy Reviews* 79: 1275–1284. https://doi.org/10.1016/j.rser.2017.05.135.

Barasa M., Bogdanov D., Oyewo A.S., Breyer C. 2018. "A cost optimal resolution for Sub-Saharan Africa powered by 100% of renewables in 2030," *Renewable and Sustainable Energy Reviews* 92: 440–457. https://doi.org/10.1016/j.rser.2018.04.110.

Barnaby F. and Kemp J., (eds.) 2007. "*Secure Energy?—Civil Nuclear Power, Security and Global Warming*," Oxford Research Group, London, www.oxfordresearchgroup.org.uk/sites/default/files/secureenergy.pdf

Battaglini A., Lilliestam J., Haas A., Patt A. 2009. "Development of SuperSmart Grids for a more efficient utilization of electricity from renewable sources," *Journal of Cleaner Production* 17: 911–918. https://doi.org/10.1016/j.jclepro.2009.02.006.

Biberacher M. 2004. "*Modeling and optimization of future energy system using special and temporal methods*," dissertation, Institute of Physics, University of Augsburg.

Barbosa L.S.N.S., Bogdanov D., Vainikka P., Breyer C. 2017. "Hydro, wind and solar power as a base for a 100% Renewable Energy supply for South and Central America," *PLoS ONE* 12: e0173820. https://doi.org/10.1371/journal.pone.0173820.

Blarke M. 2012. "Towards an intermittency-friendly energy system: Comparing electric boilers and heat pumps in distributed cogeneration," *Applied Energy* 91: 349–365. https://doi.org/10.1016/j.apenergy.2011.09.038.

Bogdanov D. and Breyer C. 2015. "Eurasian Super Grid for 100% Renewable Energy power supply: Generation and storage technologies in the cost optimal mix," *ISES Solar World Congress 2015*, Daegu, Korea, November 8–12. https://doi.org/10.18086/swc.2015.06.01.

Bogdanov D. and Breyer C. 2016. "North-East Asian Super Grid for 100% Renewable Energy supply: Optimal mix of energy technologies for electricity, gas and heat supply options," *Energy Conversion and Management* 112: 176–190. https://doi.org/10.1016/j.enconman.2016.01.019.

Bogdanov D., Koskinen O., Aghahosseini A., Breyer C. 2016. "Integrated renewable energy based power system for Europe, Eurasia and MENA regions," *5th International Energy and Sustainability Conference (IESC)*, Cologne, June 30—July 1. https://doi.org/10.1109/IESC.2016.7569508.

Bogdanov D., Farfan J., Sadovskaia K., Aghahosseini A., Child M., Gulagi A., Oyewo S., Barbosa L.S.N.S., Breyer C. 2019a. "Radical transformation pathway towards sustainable electricity via evolutionary steps," *Nature Communications* 10: 1077. https://doi.org/10.1038/s41467-019-08855-1.

Bogdanov D., Child M., Breyer C. 2019b. "Reply to 'Bias in energy system models with uniform cost of capital assumption'," *Nature Communications* 10: 4587. https://doi.org/10.1038/s41467-019-12469-y.

Blakers A., Luther J., Nadolny A. 2012. "Asia Pacific Super Grid—Solar electricity generation, storage and distribution," *Green* 2: 189–202. https://doi.org/10.1515/green-2012-0013.

Breyer C. and Knies G. 2009. "Global Energy Supply Potential of Concentrating Solar Power," *SolarPACES 2009*, Berlin, September 15–18.

Breyer C. 2012. "*Economics of Hybrid Photovoltaic Power Plants*," dissertation, Faculty of Electrical Engineering and Computer Science, University of Kassel, URN: urn:nbn:de:hebis:34-2012102242017, Pro Business, Berlin, ISBN: 978-3863863906, https://kobra.bibliothek.uni-kassel.de/bitstream/urn:nbn:de:hebis:34-2012102242017/3/DissertationChristianBreyer.pdf

Breyer C., Bogdanov D., Komoto K., Ehara T., Song J., Enebish N. 2015. "North-East Asian Super Grid: Renewable Energy Mix and Economics," *Japanese Journal of Applied Physics* 54: 08KJ01. https://doi.org/10.7567/JJAP.54.08KJ01.

Breyer C., Bogdanov D., Gulagi A., Aghahosseini A., Barbosa L.S.N.S., Koskinen O., Barasa M., Caldera U., Afanasyeva S., Child M., Farfan J., Vainikka P. 2017. "On the Role of Solar Photovoltaics in Global Energy Transition Scenarios," *Progress in Photovoltaics: Research and Applications* 25: 727–745. https://doi.org/10.1002/pip.2885.

Breyer C., Khalili S., Bogdanov D. 2019a. "Solar photovoltaic capacity demand for a sustainable transportation sector to fulfil the Paris Agreement by 2050," *Progress in Photovoltaics: Research and Applications* 27: 978–989. https://doi.org/10.1002/pip.3114.

Breyer C., Child M., Koskinen O., Bogdanov D. 2016. "A low cost power system for Europe based on renewable electricity," in: *European Utility Week*, Barcelona, November 15–17.

Breyer C., Fasihi M., Aghahosseini A. 2019b. "Carbon Dioxide Direct Air Capture for effective Climate Change Mitigation based on Renewable Electricity: A new Type of Energy System Sector Coupling," *Mitigation and Adaptation Strategies for Global Change*, in press. https://doi.org/10.1007/s11027-019-9847-y.

Breyer C., Fasihi M., Bajamundi C., Creutzig F. 2019c. "Direct Air Capture of CO2—A key technology for ambitious climate change mitigation," *Joule* 3: 2053–2057. https://doi.org/10.1016/j.joule.2019.08.010.

Brown T. W., Bischof-Niemz T., Blok K., Breyer C., Lund H., Mathiesen B.V. 2018. "Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems'," *Renewable and Sustainable Energy Reviews* 92: 834–847. https://doi.org/10.1016/j.rser.2018.04.113.

Buckminster Fuller R. 1971. "*The World Game: Integrative Resource Utilization Planning Tool. World Resources Inventory*," Southern Illinois University, Carbondale, Illinois.

Buonocore J.J., Luckow P., Norris G., Spengler J.D., Blewald B., Fisher J., Levy J.I. 2016. "Health and climate benefits of different energy-efficiency and renewable energy choices," *Nature Climate Change* 6: 100–105. https://doi.org/10.1038/nclimate2771.

Caldera U., Bogdanov D., Breyer C. 2016. "Local cost of seawater RO desalination based on solar PV and wind energy: A global estimate," *Desalination* 385: 207–216. https://doi.org/10.1016/j.desal.2016.02.004.

Chatzivasileiadis S., Ernst D., Andersson G. 2013. "The Global Grid," *Renewable Energy* 57: 372–383. https://doi.org/10.1016/j.renene.2013.01.032.

Child M., Koskinen O., Linnanen L., Breyer C. 2018. "Sustainability Guardrails for Energy Scenarios of the Global Energy Transition," *Renewable and Sustainable Energy Reviews* 91: 321–334. https://doi.org/10.1016/j.rser.2018.03.079.

Child M., Kemfert C., Bogdanov D., Breyer C. 2019. "Flexible electricity generation, grid exchange and storage for the transition to a 100% renewable energy system in Europe," *Renewable Energy* 139: 80–101. https://doi.org/10.1016/j.renene.2019.02.077.

Chin N.C. 2019. "*Could solar energy sharing between Australia and Singapore be a model for other regions?*," Eco-Business, Singapore, July 24.

Creutzig F., Ravindranath N.H., Berndes G., Bolwig S., Bright R., Cherubini F., et al. 2015. "Bioenergy and climate change mitigation: an assessment," *GCB Bioenergy* 7: 916–944. https://doi.org/10.1111/gcbb.12205.

Creutzig F., Breyer C., Hilaire J., Minx J., Peters G., Socolow R. 2019. "The mutual dependence of negative emission technologies and energy systems," *Energy & Environmental Science* 12: 1805–1817. https://doi.org/10.1039/C8EE03682A.

Czisch G. 2005. "*Szenarien zur zukünftigen Stromversorgung - Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien*," dissertation, Faculty of Electrical Engineering

and Computer Science, University of Kassel, https://kobra.bibliothek.uni-kassel.de/bitstream/urn:nbn:de:hebis:34-200604119596/1/DissVersion0502.pdf
Dahl M., Rodriguez R.A., Sondergaard A.A., Zeyer T., Andresen G.B., Greiner M.W. 2017. "Infrastructure Estimates for a Highly Renewable Global Electricity Grid," in: Schramm S., Schäfer M. (eds.) "*New Horizons in Fundamental Physics*," FIAS Interdisciplinary Science Series, Springer International Publishing, Basel. https://doi.org/10.1007/978-3-319-44165-8_25.
Deng Y.Y., Blok K., van der Leun K. 2012. "Transition to a fully sustainable global energy system," *Energy Strategy Reviews* 1: 109–121. https://doi.org/10.1016/j.esr.2012.07.003.
Dii 2012. "*2050 Desert Power—Perspectives on a Sustainable Power System for EUMENA*," Dii, Munich.
Dii 2014. "*Desert Power: Getting Connected*," Dii, Munich.
Dominik H. 1930. "*Wunschträume beim Jahreswechsel*," Beilage: Technik der Zeit, Berliner Tageblatt, Berlin, December 31.
Egli F., Steffen B., Schmidt T.S. 2019. "Bias in energy system models with uniform cost of capital assumption," *Nature Communications* 10: 4588. https://doi.org/10.1038/s41467-019-12468-z.
Epstein P.R., Buonocore J.J., Eckerle K., Hendryx M., Stout B.M., Heinberg R., Clapp R.W., May B., Reinhart N.L., Ahern M.M., Doshi S.K., Glustrom L. 2011. "Full cost accounting for the life cycle of coal," *Annals of the New York Academy of Sciences* 1219: 73–98. https://doi.org/10.1111/j.1749-6632.2010.05890.x.
[EWG]—Energy Watch Group. 2013. "*Fossil and Nuclear Fuels—the Supply Outlook*," EWG, Berlin.
Farfan J., Fasihi M., Breyer C. 2019. "Trends in the global cement industry and opportunities for a long-term sustainable CCU potential for Power-to-X," *Journal of Cleaner Production* 217: 821–835. https://doi.org/10.1016/j.jclepro.2019.01.226.
Fasihi M., Bogdanov D., Breyer C. 2015. "Economics of global LNG trading based on hybrid PV-Wind power plants," *31st EU PVSEC*, Hamburg, September 14–18.
Fasihi M., Bogdanov D., Breyer C. 2016. "Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants," *Energy Procedia* 99: 243–268. https://doi.org/10.1016/j.egypro.2016.10.115.
Fasihi M. and Breyer C. 2017. "Synthetic Methanol and Dimethyl Ether Production based on Hybrid PV-Wind Power Plants," *11th International Renewable Energy Storage Conference (IRES 2017)*, Düsseldorf, March 14–16.
Fasihi M., Bogdanov D., Breyer C. 2017. "*Overview on PtX options studied in NCE and their global potential based on hybrid PV-Wind power plants*," Neo-Carbon Energy 9th Researchers' Seminar, Lappeenranta, December 13.
Fasihi M., Efimova O., Breyer C. 2019. "Techno-economic assessment of CO_2 direct air capture plants," *Journal of Cleaner Production* 224: 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086.
Fasihi M. and Breyer C. 2020. "Baseload electricity and hydrogen supply based on hybrid PV-Wind power plants," *Journal of Cleaner Production* 243: 118466. https://doi.org/10.1016/j.jclepro.2019.118466.
Fasihi M., Weiss R., Savolainen J., Breyer C. 2020. "Global potential of green ammonia based on hybrid PV-wind power plants," submitted.
Frick M. and Thioye M. 2018. "Global Energy Interconnection," *Global Energy Interconnection* 1: 404–405. https://doi.org/10.1016/S2096-5117(18)30074-4.
[FS-UNEP] - Frankfurt School-UNEP Centre and [BNEF] - Bloomberg New Energy Finance. 2018. "*Global Trends in Renewable Energy Investment 2018*," FS-UNEP and BNEF, Frankfurt, London.
Fuss S., Lamb W.F., Callaghan M.W., Hilaire J., Creutzig F., Amann T., et al. 2018. "Negative emissions—Part 2: Costs, potentials and side effects," *Environmental Research Letters* 13: 063002. https://doi.org/10.1088/1748-9326/aabf9f.
Garcia-Valle R. and Peças Lopes J.A., eds. 2013. "*Electric Vehicle Integration into Modern Power Networks*," New York, Springer. https://doi.org/10.1007/978-1-4614-0134-6.
[GEIDCO] - Global Energy Interconnection Development and Cooperation Organization. 2018. "*Global Energy Interconnection Backbone Grids Research*," GEIDCO, Beijing, www.geidco.org
Gernaat D.E.H.J., Bogaart P.W., Vuuren van D.P., Biemans H., Niessink R. 2017. "High-resolution assessment of global technical and economic hydropower potential," *Nature Energy* 2: 821–828. https://doi.org/10.1038/s41560-017-0006-y.
Götz M., Lefebvre J., Mörs F., McDaniel Koch A., Graf F., Bajohr S., Reimert R., Kolb T. 2016. "Renewable Power-to-Gas: A technological and economic review," *Renewable Energy* 85: 1371–1390. https://doi.org/10.1016/j.renene.2015.07.066.
Gulagi A., Bogdanov D., Fasihi M., Breyer C. 2017a. "Can Australia Power the Energy-Hungry Asia with Renewable Energy?," *Sustainability* 9: 233. https://doi.org/10.3390/su9020233.

Gulagi A., Bogdanov D., Choudhary P., Breyer C. 2017b. "Electricity system based on 100% renewable energy for India and SAARC," *PLoS ONE* 12: e0180611. https://doi.org/10.1371/journal.pone.0180611.

Gulagi A., Bogdanov D., Breyer C. 2017c. "A Cost Optimized Fully Sustainable Power System for Southeast Asia and the Pacific Rim," *Energies* 10: 583. https://doi.org/10.3390/en10050583.

[GWEC]—Global Wind Energy Council. 2018. "*Global Wind Report*," GWEC, Brussels.

Haegel N.M., Atwater Jr. H., Barnes T., Breyer C., Burrell A., Chiang Y.-M., et al. 2019. "Terawatt-scale photovoltaics: Transform global energy," *Science* 364(6443): 836–838. https://doi.org/10.1126/science.aaw1845.

Hall C.A.S., Lambert J.G., Balogh S.B. 2014. "EROI of different fuels and the implications for society," *Energy Policy* 64: 141–152. https://doi.org/10.1016/j.enpol.2013.05.049.

Hansen K., Breyer C., Lund H. 2019. "Status and Perspectives on 100% Renewable Energy Systems," *Energy* 175: 471–480. https://doi.org/10.1016/j.energy.2019.03.092.

Heuser P.-M., Ryberg D.S., Grube T., Robinius M., Stolten D. 2019. "Techno-economic analysis of a potential energy trading link between Patagonia and Japan based on CO2 free hydrogen," *International Journal of Hydrogen Energy* 44: 12733–12747. https://doi.org/10.1016/j.ijhydene.2018.12.156.

Horvath S., Fasihi M., Breyer C. 2018. "Techno-Economic Analysis of a Decarbonized Shipping Sector: Technology Suggestions for a Fleet in 2030 and 2040," *Energy Conversion and Management* 164: 230–241. https://doi.org/10.1016/j.enconman.2018.02.098.

[IEA] - International Energy Agency. 2017. "*Producing Ammonia and Fertilizers: New Opportunities from Renewables*," IEA, Paris, www.iea.org/media/news/2017/FertilizermanufacturingRenewables_1605.pdf.

[IEA]—International Energy Agency. 2018. "*World Energy Outlook 2018*," IEA, Paris

[IEA-PVPS]—International Energy Agency Photovoltaic Power Systems Programme. 2018. "*Trends 2018 in Photovoltaic Applications*," IEA-PVPS, St. Ursen.

[IPCC]—Intergovernmental Panel on Climate Change. 2018. "*IPCC - Special Report on Global warming of 1.5ºC*," IPCC, Geneva, www.ipcc.ch/report/sr15/

[ITRPV]—International Technology Roadmap for Photovoltaic. 2019. "*International Technology Roadmap for Photovoltaic (ITRPV) 2018 Results*," 10th ed., ITRPV, Frankfurt a.M., March.

Jacobson M.Z. and Delucchi M.A. 2011. "Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure and materials," *Energy Policy* 39: 1154–1169. https://doi.org/10.1016/j.enpol.2010.11.040.

Jacobson M.Z., Delucchi M.A., Cameron M.A., Mathiesen B.V. 2018. "Matching demand with supply at low cost in 139 countries among 20 world regions with 100% intermittent wind, water, and sunlight (WWS) for all purposes," *Renewable Energy* 123: 236–248. https://doi.org/10.1016/j.renene.2018.02.009.

Jiang K., He C., Xu X., Jiang W., Xiang P., Li H., Liu J. 2018. "Transition scenarios of power generation in China under global 2º and 1.5ºC targets," *Global Energy Interconnection* 1: 477–486.

Justi E. 1960. "*Die zukünftige Energieversorgung der Menschheit*," Vandenhoeck & Ruprecht, Göttingen.

Khalili S., Rantanen E., Bogdanov D., Breyer C. 2019. "Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World," *Energies* 12: 3870. https://doi.org/10.3390/en12203870.

Knies G. (ed.) 2009. "*Clean Power from Deserts—The Desertec Concept for Energy, Water and Climate Security*," Whitebook 4th Ed., DESERTEC Foundation, Hamburg, www.desertec.org

Komoto K., Ito M., Vleuten van der P., Faiman D., Kurokawa K., (eds.) 2009. "*Energy from the Desert—Very Large Scale Photovoltaic Systems: Socio-economic, Financial, Technical and Environmental Aspects*," Earthscan, London.

Komoto K., Enebish N., Song J. 2013. "Very Large Scale PV Systems for North-East Asia: Preliminary project proposals for VLS-PV in the Mongolian Gobi desert," *39th PVSC*, Tampa, June 16–21. https://doi.org/10.1109/PVSC.2013.6744952.

Koskinen O. and Breyer C. 2016. "Energy Storage in Global and Transcontinental Energy Scenarios: A Critical Review," *Energy Procedia* 99: 53–63. https://doi.org/10.1016/j.egypro.2016.10.097.

Kranenburg van K., Schols E., Gelevert H., de Kler R., van Delft Y., Weeda M. 2016. "*Empowering the Chemical Industry—Opportunities for Electrification*," TNO & ECN, Hague & Petten, www.tno.nl/media/7514/voltachem_electrification_whitepaper_2016.pdf.

Krey V., Guo F., Kolp P., Zhou W., Schaeffer R., Awasthy A., Bertram C., Boer de H.-S., Fragkos P., Fujimori S., et al. 2019. "Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models," *Energy* 172: 1254–1267. https://doi.org/10.1016/j.energy.2018.12.131.

Kurokawa K. 2007. "Future direction of PV system technologies around 2030 and beyond," *PVSEC-17*, Fukuoka, December 3–7.

Li J. and Jiang S. 2018. "Global Energy Interconnection: an effective solution to climate challenges," *Global Energy Interconnection* 1: 406–408. https://doi.org/10.1016/S2096-5117(18)30075-6.

Liu Z. 2015. "*Global energy interconnection*," Academic Press, Cambridge. https://doi.org/10.1016/B978-0-12-804405-6.00008-7.

Löffler K., Hainsch K., Burandt T., Oei P.-Y., Kemfert C., von Hirschhausen C. 2017. "Designing a model for the global energy system-GENeSYS-MOD: An application of the Open-Source Energy Modeling System (OSeMOSYS)," *Energies* 10: 1468. https://doi.org/10.3390/en10101468.

Lohrmann A., Farfan J., Caldera U., Lohrmann C., Breyer C. 2019. "Global scenarios for significant water use reduction in thermal power plants based on cooling water demand estimation using satellite imagery," *Nature Energy*, in press. https://doi.org/10.1038/s41560-019-0501-4.

Mahmoudzadeh Andwari A., Pesiridis A., Rajoo S., Martinez-Botas R., Esfahanian V. 2017. "A review of Battery Electric Vehicle technology and readiness levels," *Renewable and Sustainable Energy Reviews* 78: 414–430. https://doi.org/10.1016/j.rser.2017.03.138.

Mano S., Ovgor B., Samadov Z., Pudlik M., Jülich V., Sokolov D., Yoon J.Y. 2014. "*Gobitec and Asian Super Grid for Renewable Energies in Northeast Asia*," report prepared by Energy Charter Secretariat, Energy Economics Institute of the Republic of Korea, Energy Systems Institute of the Russian Federation, Ministry of Energy of Mongolia, Japan Renewable Energy Foundation, http://www.encharter.org/fileadmin/user_upload/Publications/Gobitec_and_the_Asian_Supergrid_2014_ENG.pdf

Meisen P. 1992. *Worldwide Interconnections May Be An Idea Whose Time Has Come*, Global Energy Network Institute, San Diego, www.geni.org/globalenergy/library/technical-articles/transmission/global-energy-network/worldwide-interconnections-may-be-an-idea-whose-time-has-come/index.shtml

Oyewo A.S., Farfan J., Peltoniemi P., Breyer C. 2018. "Repercussion of large scale hydro dam deployment: The case of Congo Grand Inga hydro project," *Energies* 11: 972. https://doi.org/10.3390/en11040972.

Palm E., Nilsson L.J., Åhman M. 2016. "Electricity-based plastics and their potential demand for electricity and carbon dioxide," *Journal of Cleaner Production* 129: 548–555. https://doi.org/10.1016/j.jclepro.2016.03.158.

Perez M. and Perez R. 2015. "Update 2015—A fundamental look at supply side energy reserves for the planet," *IEA-SHCP-Newsletter* Vol. 62.

Pursiheimo E., Holttinen H., Koljonen T. 2019. "Inter-sectoral effects of high renewable energy share in global energy system," *Renewable Energy* 136: 1119–1129. https://doi.org/10.1016/j.renene.2018.09.082.

Purvins A., Sereno L., Ardelean M., Covrig C.-F., Efthimiadis T., Minnebo P. 2018. "Submarine power cable between Europe and North America: A techno-economic analysis," *Journal of Cleaner Production* 186: 131–145. https://doi.org/10.1016/j.jclepro.2018.03.095.

Ram M., Child M., Aghahosseini A., Bogdanov D., Lohrmann A., Breyer C. 2018. "A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015–2030," *Journal of Cleaner Production* 199: 687–704. https://doi.org/10.1016/j.jclepro.2018.07.159.

Ram M., Bogdanov D., Aghahosseini A., Gulagi A., Oyewo A.S., Child M., Caldera U., Sadovskaia K., Farfan J., Barbosa LSNS., Fasihi M., Khalili S., Gruber G., Fell H.-J., Breyer C. 2019a. "*Global Energy System based on 100% Renewable Energy—Power, Heat, Transport and Desalination Sectors*," study by Lappeenranta University of Technology and Energy Watch Group, Lappeenranta, Berlin, April 12, ISBN: 978-952-335-339-8.

Ram M., Aghahosseini A., Breyer C. 2019b. "Job creation during the global energy transition towards 100% renewable power system by 2050," *Technological Forecasting and Societal Change*, in press. https://doi.org/10.1016/j.techfore.2019.06.008.

Schmidt O., Hawkes A., Gambhir A., Staffell I. 2017. "The future cost of electrical energy storage based on experience rates," *Nature Energy* 2: 17110. https://doi.org/10.1038/nenergy.2017.110.

Schneider M. and Froggatt A. 2018. "*The World Nuclear Industry Status Report 2018*," Mycle Schneider Consulting, Paris, London.

Sgouridis S., Csala D., Bardi U. 2016. "The sower's way: quantifying the narrowing net-energy pathways to a global energy transition," *Environmental Research Letters* 11: 094009. https://doi.org/10.1088/1748-9326/11/9/094009.

Sörgel H. 1932. "*Atlantropa*," Fretz & Wasmuth, Zürich.

Song J. 2012. "*Cooperation with Neighboring Countries for Super-Grid in Gobi desert (SG-Gobi Project)*," International conference on Renewable Energy Cooperation and Grid Integration in North-East Asia, Ulaanbaatar, Mongolia, November 11–12.

Song J. 2014. "Super Grid in North-east Asia through Renewable Energy," *Asia-Pacific Tech Monitor* 31: 24–27.

Sorensen B. 1996. "Scenarios for Greenhouse Warming Mitigation," *Energy Conversion and Management* 37: 693–698. https://doi.org/10.1016/0196-8904(95)00241-3.

Sprengel U. and Hoyer W. 1989. "*Solarer Wassersoff—Energieträger der Zukunft*," Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR), Stuttgart.

Taggart, S., James G., Dong Z.Y., Russell C. 2012. "The Future of Renewable Linked by a Transnational Asian Grid," *Proceedings of the IEEE* 100: 348–359. https://doi.org/10.1109/JPROC.2011.2159089.

Teske S., Pregger T., Simon S., Naegler T., Graus W., Lins C. 2011. "Energy [R]evolution 2010—a sustainable world energy outlook," *Energy Efficiency* 4: 409–433. https://doi.org/10.1007/s12053-010-9098-y.

Teske S., Pregger T., Simon S., Naegler T. 2018. "High renewable energy penetration scenarios and their implications for urban energy and transport systems," *Current Opinion on Environment and Sustainability* 30: 89–102. https://doi.org/10.1016/j.cosust.2018.04.007.

Teske S. 2019. "*Achieving the Paris Climate Agreement Goals*," Springer, Cham. https://doi.org/10.1007/978-3-030-05843-2.

Tremel A., Wasserscheid P., Baldauf M., Hammer T. 2015. "Techno-economic analysis for the synthesis of liquid and gaseous fuels based on hydrogen production via electrolysis," *International Journal of Hydrogen Energy* 40: 11457–11464. https://doi.org/10.1016/j.ijhydene.2015.01.097.

Trieb F., Schillings C., Kronshage S., Viebahn P., May N., Paul C., (eds.) 2006. "*Trans-Mediterranean Interconnection for Concentrating Solar Power*," Research of German Aerospace Center (DLR) by order of Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Berlin, www.dlr.de/tt/trans-csp

Trieb F., Schillings C., Pregger T., O'Sullivan M. 2012. "Solar electricity imports from the Middle East and North Africa to Europe," *Energy Policy* 42: 341–353. https://doi.org/10.1016/j.enpol.2011.11.091.

Tzannatos E., Papadimitriou S., Koliousis I. 2015. "A Techno-Economic Analysis of Oil vs. Natural Gas Operation for Greek Island Ferries," *International Journal of Sustainable Transport* 9: 272–281. https://doi.org/10.1080/15568318.2013.767397.

[UBA] - Umwelt Bundesamt. 2016. "*Power-to-Liquids Potentials and Perspectives for the Future Supply of Renewable Aviation Fuel*," UBA, Dessau-Roßlau, http://www.lbst.de/news/2016_docs/161005_uba_hintergrund_ptl_barrierrefrei.pdf.

[UN] - United Nations. 2015. "*Sustainable Development Goals*," UN, New York, www.un.org/sustainabledevelopment/sustainable-development-goals/

Varone A. and Ferrari M. 2015. "Power to liquid and power to gas: An option for the German Energiewende," *Renewable and Sustainable Energy Reviews* 45: 207–218. https://doi.org/10.1016/j.rser.2015.01.049.

Vartiainen E., Masson G., Breyer C., Moser D., Medina E.R. 2019. "Impact of Weighted Average Cost of Capital, Capital Expenditure and Other Parameters on Future Utility-Scale PV Levelised Cost of Electricity," *Progress in Photovoltaics: Research and Applications*, in press. https://doi.org/10.1002/pip.3189.

Voigt W. 2007. "*Atlantropa. Weltbauen am Mittelmeer. Ein Architektentraum der Moderne*," Grosser+ Stein, Pforzheim.

Wang C., Dargaville R., Jeppesen M. 2018. "Power system decarbonisation with Global Energy Interconnection—a case study on the economic viability of international transmission network in Australasia," *Global Energy Interconnection* 1: 507–519.

Wang M., Kang W., Chen Z., Zhang Y., Liu C., Yang F. 2018. "Global Energy Interconnection: an innovative solution for implementing the Paris Agreement—the significance and pathway of integrating GEI into global climate governance," *Global Energy Interconnection* 1: 467–476.

[WEC]—World Energy Council and frontier economics. 2018. "*International aspects of power-to-X roadmap*," WEC Germany, Berlin.

Winemiller K.O., McIntyre P.B., Castello L., Fluet-Chouinard E., Giarrizzo T., Nam S., et al. 2016. "Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong," *Science* 351(6269): 128–129. https://doi.org/10.1126/science.aac7082.

Winter C.J. 1981. "*Wasserstoff als Sekundärenergieträger*," Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR), Stuttgart.